

## Measurement of the $pp$ analyzing power in the vicinity of 2.20 GeV

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**Abstract.** The  $pp$  elastic scattering analyzing power was measured in small energy steps in the vicinity of the accelerator depolarizing resonance  $\gamma G = 6$  at 2.202 GeV. A vertically polarized proton beam was extracted from SATURNE II at energies above the resonance and passed through different copper degraders. The beam was focused on the beam line polarimeter CH<sub>2</sub> target. Its halo was removed by four powerful magnets. Measurements at degraded energies were complemented by data obtained with the directly extracted polarized beam outside the resonance region. Analyzing power results at fixed laboratory angles are compared with existing data in the region under discussion, with polynomial fits from 1.6 to 3.5 GeV, and with phase shift analysis predictions.

### 1 Introduction

The experiment was carried out in the framework of the Nucleon–Nucleon (NN) program at SATURNE II. Its aim was to obtain the  $pp$  elastic scattering analyzing power  $A_{\text{ono}}$  in the kinetic energy region close to the the accelerator depolarizing resonance  $\gamma G = 6$  at 2.202 GeV. This resonance is usually crossed by a spin flip at strong focusing accelerators. The beam polarization varies strongly within the resonance region, and the interval from 2.185 to 2.215 GeV cannot be reached. For this reason the extracted energy was fixed above the resonance and was decreased by Cu degraders. We assumed that passage of the beam through the degraders does not affect the beam polarization  $\vec{P}_B$ . This was checked outside the depolarizing resonance region, where several points were measured under different conditions. The NN beam line polarime-

ter PL1 [1,2] was used to determine the  $pp$  elastic scattering analyzing power  $A_{\text{ono}}$  at fixed laboratory angles  $\theta_{\text{lab}} = 11.6^\circ, 13.9^\circ, 16.1^\circ$ , and  $18.4^\circ$ .

The present results are compared with the interpolated values from existing measurements [3–11], with the former fits to data from 1.6 to 3.5 GeV at the two smallest angles [12], and with the predictions of the Virginia Polytechnic Institute energy dependent phase shift analysis [13] (VPI-PSA).

We use the nucleon–nucleon notation from [14], where the subscripts of any observable  $X_{pqij}$  refer to the polarization states of the scattered, recoil, beam, and target particles, respectively. Since the target was unpolarized and polarizations of outgoing particles were not analyzed, only the beam spin index  $i$  remained. The polarizations of the incident particles in the laboratory system are oriented along the basic unit vectors  $\vec{k}$ ,  $\vec{n} = [\vec{k} \times \vec{k}']$ ,  $\vec{s} = [\vec{n} \times \vec{k}]$ , where  $\vec{k}$  and  $\vec{k}'$  are the beam and scattered particle directions, respectively, and  $\vec{n}$  is the normal to the scattering plane.

$\vec{P}_B$  was oriented along the vertical direction and its sign changed every accelerator spill, whereas  $|P_B|$  remained the same [15]. The particles were scattered on a CH<sub>2</sub> target and the asymmetry of the counts  $N^+$  and  $N^-$ , recorded with  $\pm|P_B|$ , respectively, yielded

$$\epsilon(\text{CH}_2) = (N^+ - N^-)/(N^+ + N^-) = A(\text{CH}_2) \cdot P_B. \quad (1)$$

Here  $A(\text{CH}_2)$  is the analyzing power of the target. For individual events, the azimuthal angle of the detectors

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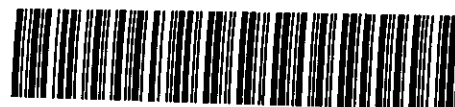
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**Table 1.** The analyzing power  $A_{oono}$  in  $pp$  elastic scattering. The Cu degrader thickness is given for the extracted beam energy in each group. Errors of experimental values contain very small statistical uncertainties ( $\leq \pm 0.003$ ), random-like errors from partial result dispersions, and systematic errors ( $\sim \pm 5\%$ ) due to the angular bin width of  $\pm 1^\circ(\ell ab)$ . The different errors were added in quadrature. The relative normalization error on  $\Delta P_B$  (not included) is  $\pm 3\%$ . In addition, at  $16.1^\circ$  and  $18.4^\circ$  a common multiplicative factor ranging from 1.00 to 1.10 may move all data of a given set together

$T_{kin}$ (GeV)	Cu (cm)	$\theta_{lab} = 11.6^\circ$		$\theta_{lab} = 13.9^\circ$		$\theta_{lab} = 16.1^\circ$	
		$\theta_{CM}$ (deg)	$A_{oono}(pp)$	$\theta_{CM}$ (deg)	$A_{oono}(pp)$	$\theta_{CM}$ (deg)	$A_{oono}(pp)$
2.258	out	33.9	$0.254 \pm 0.013$	40.3	$0.190 \pm 0.010$	46.4	$0.138 \pm 0.007$
2.219	3.0	33.7	$0.303 \pm 0.014$			46.2	$0.152 \pm 0.007$
2.206	4.0			40.1	$0.190 \pm 0.010$	46.1	$0.139 \pm 0.008$
2.180	6.0	33.6	$0.264 \pm 0.014$	40.0	$0.203 \pm 0.011$	46.0	$0.153 \pm 0.009$
2.250	out	33.9	$0.266 \pm 0.013$	40.3	$0.202 \pm 0.011$	46.3	$0.136 \pm 0.007$
2.224	2.0	33.8	$0.229 \pm 0.017$	40.2	$0.182 \pm 0.013$	46.2	$0.142 \pm 0.007$
2.217	2.5	33.7	$0.256 \pm 0.014$	40.2	$0.217 \pm 0.011$	46.2	$0.141 \pm 0.007$
2.211	3.0	33.7	$0.257 \pm 0.013$	40.1	$0.206 \pm 0.010$	46.1	$0.140 \pm 0.007$
2.205	3.5	33.7	$0.265 \pm 0.014$	40.1	$0.205 \pm 0.010$	46.1	$0.142 \pm 0.007$
2.198	4.0	33.7	$0.271 \pm 0.014$	40.1	$0.209 \pm 0.011$	46.1	$0.142 \pm 0.007$
2.305	out	34.1	$0.263 \pm 0.013$	40.6	$0.217 \pm 0.012$	46.6	$0.137 \pm 0.007$
2.279	2.0	34.0	$0.260 \pm 0.013$	40.4	$0.204 \pm 0.011$	46.5	$0.138 \pm 0.007$
2.253	4.0	33.9	$0.267 \pm 0.013$	40.3	$0.211 \pm 0.011$	46.4	$0.135 \pm 0.007$
$T_{kin}$ (GeV)	Cu (cm)	$\theta_{lab} = 11.6^\circ$		$\theta_{lab} = 16.1^\circ$		$\theta_{lab} = 18.4^\circ$	
		$\theta_{CM}$ (deg)	$A_{oono}(pp)$	$\theta_{CM}$ (deg)	$A_{oono}(pp)$	$\theta_{CM}$ (deg)	$A_{oono}(pp)$
2.100	out	33.3	$0.275 \pm 0.014$	45.6	$0.162 \pm 0.009$	51.7	$0.109 \pm 0.006$
2.175	out	33.6	$0.287 \pm 0.014$	46.0	$0.158 \pm 0.008$	52.1	$0.120 \pm 0.006$
2.225	out	33.8	$0.308 \pm 0.016$	46.2	$0.186 \pm 0.010$	52.4	$0.087 \pm 0.005$
2.272	out	33.9	$0.279 \pm 0.014$				
2.297	out	34.0	$0.276 \pm 0.014$				

where  $T$  is in GeV. The fit describes 28 contributing points with  $\chi^2 = 14.97$  and is shown in Fig. 1.

The linear fit to  $A_{oono}(13.9^\circ)$  data yielded

$$A_{oono}(13.9^\circ) = (0.623 \pm 0.012) - (0.180 \pm 0.005) \cdot T. \quad (5a)$$

It describes 75 contributing points with  $\chi^2 = 90.28$ .

The quadratic fit to the same data yielded

$$A_{oono}(13.9^\circ) = (0.798 \pm 0.074) - (0.331 \pm 0.063) \cdot T + (0.032 \pm 0.013) \cdot T^2, \quad (5b)$$

with  $\chi^2 = 87.39$  and it is shown in the same figure. Note that the contribution of the quadratic term in (5b) is weak and its error is  $\pm 41\%$ . The difference between the two fits (5a) and (5b) is negligible.

Using  $\epsilon(pp)$  and the  $A_{oono}$  value at one given angle we obtain  $P_B$ . Since it is independent of the polarimeter scattering angle  $\theta_{lab}$ , the same  $P_B$  value may be used to obtain  $A_{oono}$  values at other angles, if the ratio  $R$  is known.

### 3 Results and discussion

The  $A_{oono}(pp)$  data are given in Table 1 where they are divided into four groups. The data of each of the first three groups were taken with a fixed extracted beam energy. The energy was reduced by inserting different Cu degraders with thicknesses shown in the table. The degraded energies were corrected by the beam spot position, if necessary. The last group was measured with an extracted beam only. Statistics of counts at each angle and energy varied from  $2 \cdot 10^5$  to  $10^8$  in both polarimeter arms. The beam polarization was deduced from dedicated measurements at  $13.9^\circ(\ell ab)$  at energies where no degraders were used.

At  $16.1^\circ$  and  $18.4^\circ$  the factor  $R$  of (3) has been assumed to be the same as at  $13.9^\circ$ . This assumption introduces an additional common uncertainty of less than 10%.

Errors on the experimental values contain statistical uncertainties and systematic errors due to the angular bin width of  $\pm 1^\circ(\ell ab)$ . The normalization error  $\Delta P_B$  is  $\pm 3\%$ .

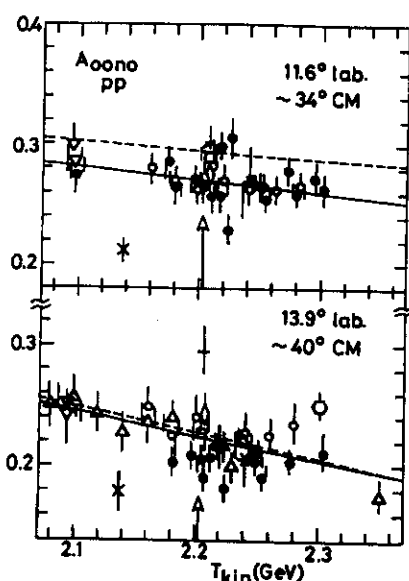


Fig. 1.  $A_{\text{ono}}$  energy dependence at  $11.6^\circ(\text{lab}) \sim 34^\circ(\text{CM})$  and  $13.9^\circ(\text{lab}) \sim 40^\circ(\text{CM})$ . The meaning of the symbols is as follows.  $\bullet$  is for this experiment,  $\nabla$  for [3],  $\circ$  for [4],  $\Delta$  for [5],  $\star$  for [6],  $+$  for [7],  $\times$  for [8], hexagon for [9],  $\diamond$  for [10], an open square for [11]; arrows are for the depolarizing resonance energy, solid curves for fits referring to [12] and dashed curves for VPI-PSA [13]

The results for the two smaller angles are plotted in Fig. 1 and for the larger angles in Fig. 2. Existing data in the energy region from 2.08 to 2.36 GeV are shown. The ANL-ZGS data [7–11] are plotted without normalization factors as recommended in [16]. The arrows in the figures denote the energy of the accelerator depolarizing resonance. The nominal ZGS energies cannot be taken literally, since the uncertainty in beam momentum was relatively large ( $\sim \pm 3.5\%$ ). The solid lines in Fig. 1 represent the fits (4) and (5b) to all previously existing data over the region from 1.6 to 3.5 GeV [12] (Sect. 2). The dashed curves in both figures are the predictions of VPI-PSA [13], where the present data were included. Both curves are in excellent agreement at  $13.9^\circ$ . The PSA predictions at other angles give systematically larger  $A_{\text{ono}}$  values than the majority of the data points.

In general, no PSA represents an ideal tool for the absolute beam polarimetry. This is simply due to the goal of a PSA, which is to describe the angular dependence of all independent observables together. Such a description depends, among other things, on the number of free phase shifts. For an energy dependent PSA, in addition, the prediction at one energy depends on data in a large energy region and local structures may be averaged away.

Note that the laboratory angles  $16.1^\circ$  and  $18.4^\circ$  were used to monitor the beam polarization at low energies. They are not a good choice for a  $pp$  polarimeter setting between  $T_{\text{kin}}$  from 1.5 to 3 GeV. The  $A_{\text{ono}}(pp)$  value around  $16.1^\circ$  strongly depends on the angle. Around  $18.4^\circ$  and above 2 GeV, the analyzing power is close to its first min-

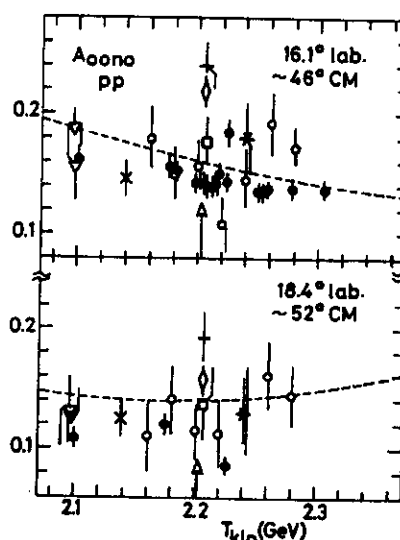


Fig. 2.  $A_{\text{ono}}$  energy dependence at  $16.1^\circ(\text{lab}) \sim 46^\circ(\text{CM})$  and  $18.4^\circ(\text{lab}) \sim 52^\circ(\text{CM})$ . The meaning of the symbols is the same as in Fig. 1

imum [17]. This can be seen for the latter angle from the VPI-PSA prediction in Fig. 2.

## 4 Conclusions

The present results agree well with existing data and complete the information necessary for beam polarization measurements. They show no anomaly in the  $pp$  analyzing power energy dependence in the region of the strong depolarizing resonance  $\gamma G = 6$ . Our results suggest that energy degraders may be used in the otherwise forbidden interval over the depolarizing resonance width. In this special case the fits to the analyzing power data at small angles provide a better description than the PSA predictions.

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